

REMARKS/ARGUMENTS

Reconsideration of the application is requested.

Claims 36-42, and 45-82 are now in the application. The amendment is outlined as follows:

- Claim 1 has been canceled and replaced with the new claim 82. Besides some formalistic changes, claim 82 now positively recites that the greenfoils are formed of piezoelectric ceramic material.
- Claims 2-35 have been canceled and replaced with the new claims 48-81. The new claims largely correspond with the original claims 2-35, but they have been corrected for obvious transcription errors. Several of the formulas, most notably the formula appearing in the original claim 34 (now claim 80), have been corrected. The new claims 48-81 now depend from claim 47.
- Claim 47 largely corresponds to the original claim 1 in this application. Applicants are returning to the original request because, after reviewing all of the references of record, we have come to the conclusion that claim 47 is patentable. As will become clear from the following discussion, specific emphasis is placed on the term "monolithic."

- The method claims 36-42 remain withdrawn from consideration.

The withdrawn claims will be appropriately pursued at a later time, together with the canceled claims 43 and 44.

The replacement of most of the claims has become necessary because applicants found some discrepancies in the internal files and could not determine, with certainty, the actual status of the claims. The Examiner's cooperation in reviewing the claims in detail for any possible further errors will be greatly appreciated.

Enclosed herewith is a copy from Webster's Third International Dictionary which explains the word "monolithic." Webster's provides examples according to which monolithic means "formed or carved from a single block of stone," "cast as a single piece," or "constituting one massive undifferentiated whole exhibiting solid uniformity often without diversity or variability." The term "monolithic," as referenced in Webster's, is utilized much in the same way in applicants specification. It is a well known principle of patent law that, when applicants do not provide a definition of a term that distinguishes the term from the generally accepted and typical definition, then Webster's and similar dictionaries may be used to elucidate the meaning of a term. In this case, the specification does not provide a different definition and

we therefore are bound to the generally excepted definition. Claim 47, therefore, defines a uniform or solid massive and undifferentiated whole that exhibits solid uniformity and often does not show diversity or variability. We will return to this issue in the following discussion of the prior art.

This brings us to the first art rejection, in which claims 1 and 13 have been rejected as been anticipated by Harada et al. (U.S. 5,233,260) under 35 U.S.C. § 102(b). While the Examiners arguments and explanation concerning the product-by-process terminology are appreciated, we nevertheless traverse on the basis of, and with emphasis on, the claim term "monolithic" in the context of the combination as claimed.

The reference Harada details a state of the art (i.e., Harada's prior art) in which a piezoelectric multilayer actuator is produced. The ceramic green foils are commonly sintered at a temperature of approximately 1300°C (col. 1, lines 62-65). This very high sintering temperature, in Harada's prior art, defines the choice of metals for the inner electrodes. The inner electrodes have to be stable at the high temperatures and they must not melt. In Harada's prior art, therefore, the electrodes are formed of an alloy of silver and palladium. Col. 1, lines 66-68. According to Harada, the thus-described prior art is problematic and disadvantageous because

silver ions migrate out from the silver of the electrode and lead to short circuits between the electrodes. Col. 2, lines 1-15.

In order to solve the problem concerning silver migration or silver ion migration, the reference Harada discloses a piezoelectric multilayer actuator in which the inner electrodes are formed with nickel or copper. Col. 2, lines 41-46.

Due to the lower melting point of the electrode metals, Harada is forced to step away from the common sintering of the piezoelectric component in a stack of layered green foils. The melting point of copper, of course, lies at 1083°C and the sintering temperatures as they are required by the state of the art are much too high and they would melt the copper. Harada, therefore, proposes to stack already sintered piezoelectric foils which may already be provided with a copper-containing metal film. Col. 4, line 64-68. Thereafter, the metallized ceramic layers may then be pressed together and the adhesion may even be reinforced with heat treatment. The reference makes it very clear, however, how the product is formed:

[T]he process for preparation of stack-type piezo-electric elements of the present invention comprises stacking layers of a sintered piezoelectric ceramic

material and electrode layers alternately, and then heating, or heating under pressure, the stacked layers at a temperature lower than the sintering temperature of the piezoelectric ceramic material.

Harada, col. 5, line 17-23. The best bonding disclosed by Harada is diffusion bonding that may or may not happen between the individual layers.

This is now the crux of the invention. Harada discloses a piezoelectric component in which individually sintered and subsequently metalized ceramic forms are stacked on top of one another and in which a subsequent tempering step does not reach the sintering temperature of the ceramic material. Harada thusly gets around its prior art in which the stacked three layer electrode sandwich is commonly sintered at a temperature of 1300° C.

This succinct summary of the Harada disclosure also immediately points to the difference with regard to the claimed invention. As noted above, we claim a monolithic stack which is formed of several layers. The monolithic stack is attained by common sintering of stacked ceramic green foils similarly to Harada's prior art. The term "monolithic," again, means that the stack or the component is formed of a single piece, that it is a single block, or that it has a single piece which forms an indivisible unit. In the pertinent technology which deals with ceramics and layered

stacks of ceramics and metal electrodes, it is further clear that a "monolithic" component is formed in a uniform and common process. The ceramic green foils which are sintered after stacking become one after sintering at certain locations where there is no closed intermediate electrode layer or metal layer to separate the ceramics. Where the ceramic green foils touch each other without intermediary they will, during the sintering process, fuse into one another to form a uniform structure without diversity or variability (cf. Webster's). That is, we arrive at the same result at those locations where the intermediate metal is not present, as if the ceramic had been formed as a green compact prior to sintering without any distinction between the "layers."

The first conclusion is clear: Harada teaches away from the monolithic component. As explained above, Harada distinguishes itself from the monolithic formation that is reached by the common sintering of several green layers and instead describes a piezoelectric component in which already-sintered layers are stacked on top of one another. The reference teaching, therefore, does not lead to a component of a uniform block. Instead, individual ceramic layers are interconnected by metallic inner electrodes and the connection is reinforced by a pressure application and heating (below the

sintering temperature). Harada makes sure to define the critical terminology:

The term "sintered piezoelectric ceramic" referred to herein means the product obtained by sintering a piezoelectric ceramic green sheet.

Col. 5, lines 26-29. While Harada does arrive at a block which forms a unitary structure, these sintered piezoelectric ceramics form individual layers that are easily distinguished from one another because they have been sintered prior to interconnecting the same. That is, Harada has several ceramic layers which are glued to one another.

A component that is produced in accordance with Harada shows substantial functional disadvantages as compared to a piezo stack that is produced according to the invention and that is formed as a monolithic piezo stack. A primary disadvantage is found in the production in that during the stacking of already-sintered layers they are subject to minimum mechanical requirements. These sintered and thus rigid layers, must be mechanically so stable, as to allow them to be handled during the further manufacture and they need to at least support themselves. A minimum thickness of typically at least 500  $\mu\text{m}$  is necessary (cf. Table 5 in the original specification, where ceramic samples at that thickness and even greater thickness are described).

In contrast, the novel piezo stack that is formed as a monolithic stack allows considerably smaller layer thicknesses for the finished ceramic layers, because they are processed in the form of a green foil which is provided with a binder and they are thus very easily bendable and there certainly does not exist any danger of breaking. Thicknesses of down to 20  $\mu\text{m}$  or even lower are thus possible.

Smaller layer thickness in the ceramics are, of course, advantageous in that the space in between the inner electrodes is much smaller. By definition, the field strength of the electrical field depends on the potential difference between the electrodes and the spacing distance between the electrodes ( $E = V/d \rightarrow$  *localized electric intensity equals the potential difference  $V$  between plates spaced apart by  $d$* ). It is immediately clear that if the voltage is not changed, a smaller distance between the electrodes leads to an increase in the electrical field. Similarly, of course, the same electrical field strength can be attained by much lower voltages if the spacing distance is reduced. It is further known that the deflection of a piezoelectric layer is nearly directly proportional to the electrical field. That means, then, that in order to reach a given amount of deflection, which is indeed the important aspect here, it is primarily important that in the monolithic production of the piezo stack



with the much smaller spacing distance between the electrodes, a much smaller operating voltage suffices.

In summary, Harada does not anticipate the invention of claim 47 or any of the other claims, because Harada does not disclose a monolithic stack of ceramic and electrode(s) with copper.

All of the claims were further rejected as being anticipated by Kato et al. (US 6,266,230 B1, Kato) under 35 U.S.C. § 102(e), and as being obvious over modifications of the teaching of Kato under 35 U.S.C. § 103. We respectfully traverse.

The rejections under § 102 and § 103 are discussed in common in the following because Kato can be eliminated as a viable reference. Kato, as will be shown, does not belong to the art of piezoelectric devices and the very core principle of piezoelectric ceramics (e.g., controlled deflection) on which the invention is based is in fact avoided by Kato. In other words, Kato belongs to a different class of devices and Kato teaches away from the invention.

The first impression with Kato's disclosure is that the inner copper electrodes are only scantily described and the

disclosure is quite limited to finding cheaper replacement materials for silver and palladium, such as copper for the inner electrodes. See, for example, claim 4 and column 12, lines 39-45, following the exemplary embodiment dealing with "inexpensive multilayer capacitors" and sintering temperatures of below 1150°C. Kato is concerned with multilayer capacitors. While the ceramic material is indeed a lead-containing ceramic - similar to compositions that are suitable for piezoelectric devices (col. 4, lines 4-18) - the gist of Kato points in the opposite direction. Kato tries to avoid piezoelectric effects. Such mechanical conversions, in the context of Kato, are losses and should be avoided.

Specifically, the Kato capacitor should not have and does not have piezoelectric characteristics - at least in the design temperature range. In Kato's words:

[T]he temperature at which a dielectric . . . has its dielectric constant peak, i.e. the Curie temperature is allowed to be below -50° C. Therefore, piezoelectricity is not induced even when a DC bias voltage is applied, thus enabling a multilayer capacitor having no loss caused by excitation of unwanted resonance to be produced using inexpensive electrode metal.

Kato, col. 4, lines 56-63. The Curie temperature, of course, is the temperature at which, upon being exceeded, the piezo characteristics of the ceramic are lost. As noted above, piezoelectric losses are to be avoided - which is certainly a

viable object in the context of electric capacitors. Much in contrast, of course, in the context of piezoelectric devices, such "losses" are indeed the very functionality of the device.

According to Kato, the Curie temperature comes into play once again in the context of replacing the expensive inner electrodes with inexpensive electrodes (e.g., copper) of the reference. In the case of the inexpensive multilayer capacitor, however, two important requirements have to be met.

Kato explains:

Besides the compositions indicated in Table 1 used in the example, when dielectric compositions that can be baked at a temperature below 1150°C. and have a Curie point below -50°C. are used, inexpensive multilayer capacitors can be obtained in which the loss is not increased extremely by the application of a DC bias voltage or a large-amplitude alternating current.

Col. 12, lines 39-44. The assembly can be baked at below 1150°C and the Curie temperature must be below -50°. This, again, leads away from the claimed invention. The effects sought and obtained by the claimed invention are avoided by the Kato teachings.

The invention of the new claim 47 provides for a piezoelectric device. It is understood that the claimed device has to exhibit piezoelectric characteristics at normal temperatures, such as room temperature. As detailed in the specification,

therefore, the Curie temperature of the ceramics provided here is disclosed at 339°C. Applicants thus clearly and unambiguously direct the focus of the invention on the characteristics that are defined by the Curie temperature. The piezoelectric behavior of applicants' device and materials is observed at room temperature and slightly above. Kato does not suggest such a device, and Kato quite teaches away from such behavior.

The secondary references Tsunooka et al. and Seo provide for additional and pertinent teachings. However, neither reference makes up for the "shortcomings" of Kato which, as noted above, has been disqualified as a viable reference. Neither Tsunooka et al. nor Seo can properly modify Kato to point to the claimed invention.

In summary, neither Harada nor Kato, nor any other reference of record, whether taken alone or in any combination, either shows or suggests the features of the claims. All of the claims, including the dependent claims are believed to be patentable.

In view of the foregoing, reconsideration and allowance of claims 1-33, 35-42, and 45-48 are solicited.



Appl. No. 09/736,266

Amdt. dated February 10, 2004

Reply to Office action of September 15, 2003

Petition for extension is herewith made. The extension fee for response within a period of two months pursuant to Section 1.136(a) in the amount of \$420.00 in accordance with Section 1.17 is enclosed herewith.

Please charge any other fees which might be due with respect to Sections 1.16 and 1.17 to the Deposit Account of Lerner and Greenberg, P.A., No. 12-1099.

Respectfully submitted,

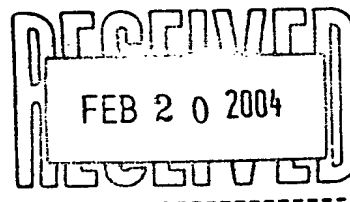
For Applicants


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February 10, 2004

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: of, relating to, or characterized by monoleism  
 : having a eous rock ire MONO- GENETIC by either character nogenesis f one sex  
 + -gen + have de- ancestral  
 ist] : one  
 monoge-  
 pus] : of  
 1 a : the POLYGENY + -genie  
 + -glot] language  
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 ride] : an yl groups e beta- or  
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 1; mono- gram (al-  
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mono-ion \i= at MONO- + \ n [mon- + ion] : an ion having only one charge  
 mono-isotopic \"+\ adj [mon- + isotopic] : consisting of a single isotope — used of an element  
 mono-ketone \"+\ n [mon- + ketone] : a chemical compound containing one ketonic carbonyl group  
 mo-nol-a-ter \mə'näləd-ə(r)\ also mo-nol-a-trist \-lə-träst\ n -s [monolatry + -er or -ist] : one whose religious practices are typified by monolatry  
 mo-nol-a-trous \-ə-trəs\ adj [monolatry + -ous] : of or relating to monolatry  
 mo-nol-a-try \-ə-trē\ n -s [mon- + -latry] : HENOTHEISM  
 mono-layer \i= at MONO- + \ n [mon- + layer] : a single continuous layer or film that is one cell or molecule in thickness  
 1 mono-line \"+\ adj [mon- + line (n.)] : having or relating to a single line: as a : writing only one main branch of insurance — compare MULTIPLE-LINE b : MONORAIL  
 2 monoline \"+\ n [mon- + line] : MONORAIL  
 1 mono-lingual \i= at MONO- + \ adj [mon- + lingual] : expressed in or knowing or using only one language  
 2 monolingual \"+\ n -s : a person who understands and speaks only one language  
 mono-literal \"+\ adj [mon- + literal] 1 : consisting of one letter 2 a : using single letters as cipher equivalents b : MONO-GRAPHIC — mono-literally \"+\ adv  
 1 mono-lith \mān'lith, 'mōn-\ n -s [F monolithe, fr. monolithe, adj., monolithic, fr. L monolithus, fr. Gk monolithos, fr. mon- + lithos stone] 1 a (1) : a single great stone often in the form of an obelisk or column (the 120-ton ~s on three sides of the choir altar — Amer. Guide Series: Maine) — compare MEGALITH (2) : something resembling a monolith and usu. having tremendous size or strength : COLOSSUS (weld together even more tightly the parallel ~s of party and state — Time) (his friends see him as a pillar of determination; his enemies consider him a thick-skinned ~ — Newsweek) b (1) : a single large block of concrete serving a specific purpose (2) : one of many large blocks cast in place to form gravity-type concrete dams 2 : a mountain or large hill apparently composed of one kind of rock usu. of a coarse-grained igneous rock 3 : a column of soil several feet deep removed as a unit  
 2 monolith \"+\ adj [F monolithe] : MONOLITHIC  
 mono-lith-ic \i=, lithik, -thēk\ adj [F monolithe or L monolithus monolithic + E-ic] 1 a : formed or carved from a single block of stone b : made up of monoliths (Stonehenge is a ~ monument) 2 a : consisting of one stone — used of the shaft of a column not built up of drums b : having a type of architecture or construction depending upon rock cutting or excavation from the solid rock 3 a of a concrete structure : cast as a single piece b of a concrete floor or pavement : having a special quality surface layer which is applied while the bottom layer is still green so that both layers harden to form an integral unit 4 : constituting one massive undifferentiated whole exhibiting solid uniformity often without diversity or variability (have rejected the idea of the domination of the single ~ party — John Dewey) (a ~ commercial enterprise — Atlantic)  
 mono-lith-ism \i=, lithizəm\ n -s [F monolithisme, fr. monolithe + -isme -ism] : the quality or state of being monolithic (where political ~ inevitably leads — Saturday Rev.)  
 mono-lithologic \i= at MONO- + \ adj [mon- + lithologic] : composed of but one kind of rock  
 mono-lobular \"+\ adj [mon- + lobular] : having one lobe  
 mono-locular \"+\ adj [ISV mon- + locular] : UNILOCULAR  
 mono-log-ic \mān'lajik\ or mono-log-i-cal \-jəkal\ adj [monology + -ic, -ical] : of, relating to, or characteristic of a monologue (voice . . . mounted from a ~ mutter to a high-toned harangue — L.C. Douglas)  
 mo-nol-o-gist \mə'näləjəst, in sense 3 " also 'mān'l,ŏg- or -l,äg- sometimes 'mōn'l, -\ n -s 1 : one who soliloquizes 2 : one who monopolizes conversation 3 : a performer of monologues (greatest ~s in modern minstrelsy — C.F. Withe)  
 mo-nol-o-gize \mə'nälə,jīz also 'mān'l,ŏ,gīz or -l,äg- sometimes 'mōn'l, -\ also mon-o-logu-ize \i=, -\ vi -ED/-ING/-S [monology + -ize] : to utter a monologue : SOLILOQUIZE

AMINE 1  
 mono-methylolurea \NL-urea] : METHYLOL  
 mono-metric \"+\ adj : more at MEASURE] : 1  
 mono-metrical \"+\ adj : metrical, metric] : relati  
 mo-no-mi-al \mə'nōmī-al] : a mathematical e  
 monomial \"+\ adj 1 : sisting of a single word c a plant or animal  
 mono-mict \i= at MON mon- + Gk miktos mixe at MIX] : relating to a single mineral species —  
 mono-mineral \"+\ adj [ISV mon- + orig. formed as Ger mc almost wholly of a singl  
 mono-molecular \i= a : relating to or consisti compound> : being only layer> : UNIMOLECULAR  
 mono-mo-ri-um \i=, m morion part, portion, dir : a large widely distrib tant household pests —  
 mono-morphemic \i= c : consisting of only one  
 mono-mor-phic \i=, mō [mon- + -morphic, -moi : exhibiting the same c members — used esp. of : same form throughout v of an ametabolic insect — used of a primitive 3 : producing spores of  
 mono-mor-phism \i=, m being monomorphic  
 mono-my-ar-ia \i=, mī' pl; cap [Monomyaria, N. NL, fr. mon- + -mya] : Lamellibranchia compri pearl oysters, and scallo compare DIMYARIA — m or n  
 mon-onch \mā,nəŋk, 'n of the genus Mononchus  
 mo-non-chus \mə'nəŋk (modif. of Gk onkos bart of predatory nematodes single pharyngeal tooth where they have been est to the acre  
 mono-neural \i= at M muscle : receiving brancl  
 mo-non-ga-he-la \mə,n [fr. Monongahela river and : northern West Vir : American whiskey; sp Pennsylvania  
 mono-nitrate \i= at MO pound containing a sing CH<sub>2</sub>ONO<sub>2</sub>>  
 mono-nitrated \"+\ a nitrate, v.] : modified by one nitrate group  
 mono-nitration \"+\ n ] of modifying by the intr nitrate group  
 mono-nitro \"+\ adj ] : containing one nitro gr  
 mon-ont \mā,nənt, 'mō, mono-nuclear \i= at M

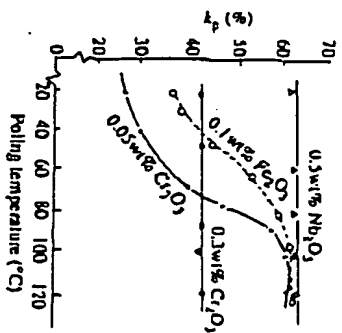


Fig. 3.14. Dependence of  $k_p$  on the poling temperature in PZT ceramics with different dopants. Poling field of 5 kV/cm and poling time of 60 min were fixed (after Takahashi et al. [38]).

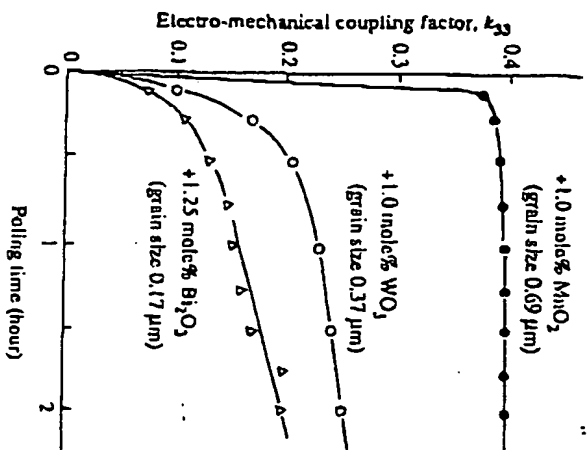


Fig. 3.15. Dependence of the coupling factor  $k_{33}$  in  $\text{PbTiO}_3$  ceramics with different grain size caused by different dopants (after Ueda et al. [20]).

leakage current would result in sample breakdown during the period of poling. Figure 3.16 shows the results of poling experiments in  $\text{PbTiO}_3$  ceramics. The coupling factor  $k_{33}$  has a sensitive dependence on the poling temperature. However, above 200°C the breakdown occurs more easily. In general, for poling most of the lead-system piezoelectric ceramics, a field of

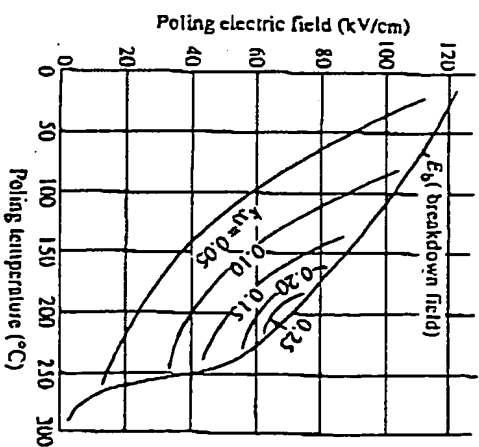


Fig. 3.16. Dependence of  $k_{33}$  coupling factor of  $\text{PbTiO}_3$  ceramic on poling field and poling temperature. Breakdown field depends on temperature (after Ueda et al. [20]).

2.5 to 4.5 kV/cm is usually sufficient, and a poling temperature of 100–170°C and a poling time of 10–30 min are used.

When poling a large-sized sample, it is difficult to set up a poling apparatus with very high voltage (e.g. 200 kV for poling a sample with an electrode separation of 5 cm). A high-temperature poling technique has been applied in poling a piezoelectric ceramic transformer (with an electrode separation of about 6 cm) [39]. The poling procedure is as follows: The ceramic sample is heated up to above the Curie point (about 400°C) in air, and then a poling field of about a tenth of a 'normal' poling field is applied on the sample, in spite of a small leakage current (about a few mA). Afterwards, one lets the temperature drop down to room temperature with the field still on. The field is then removed at room temperature and the poling process is concluded. This method is used frequently for poling ferroelectric single crystals.

### 3.2. Compositions and modifications of piezoelectric ceramics

#### 3.2.1. Effects of the composition and grain size on properties

##### 3.2.1.1. Lead zirconate titanate

Lead zirconate titanate (PZT) is a main industrial product among piezoelectric ceramic materials that have excellent piezoelectric properties. In

fig. 3.6, we see that there corresponds to the morphotropic phase boundary, the ratio  $53/47$  for  $Zr/Ti$  in a  $xPbZrO_3-(1-x)PbTiO_3$  pseudo-binary system at room temperature. In figs. 3.8 and 3.9, we see that ceramics with compositions near the morphotropic phase boundary have anomalous dielectric and piezoelectric properties. In general, the structure with a composition at the morphotropic phase boundary is considered as a special transitional structure between the tetragonal and the rhombohedral (trigonal) phases. The lattice structure may be changed by an external field, i.e., a phase transition from tetragonal to rhombohedral (trigonal) or from rhombohedral to tetragonal can be caused by an electric field [40]. Therefore, this special structure is favorable for displacement of  $Ti^{4+}$  ions and poling. To explain why maximum piezoelectric activity occurs at the tetragonal-rhombohedral morphotropic phase boundary, a thermodynamic analysis has been suggested [41-43].

Depending upon the specific requirements for different applications of piezoelectric ceramics, various compositions of the PZT system (or say, the ratio  $Zr/Ti$ ) may be chosen. For example, if a material with a high value of  $k_p$  and a high value of permittivity is desired, a composition near the morphotropic phase boundary should be chosen [44]. On the other hand, if a material with a high mechanical quality  $Q_m$  and a low permittivity is desired, a composition far away from the morphotropic phase boundary should be chosen. Thus, properties of ceramics may be changed by changing the ratio  $Zr/Ti$ .

The grain size in piezoelectric ceramics depends on the material composition and the sintering process. In general, the average grain diameter in fine-grain ceramics is about  $1\ \mu$  or less, and that in coarse-grain ceramics is about  $6-7\ \mu$ . When some metal oxides are doped into PZT ceramics, grain growth in the ceramics may be restrained. For example, an experiment showed that in the case of PZT ceramics sintered at  $1500^\circ C$  for 5 h, an average grain diameter of  $5.5\ \mu$  and a  $Q_m$  of 300 were obtained in undoped samples, while an average grain diameter of  $2.7\ \mu$  and a  $Q_m$  of 900 were obtained in samples doped with  $0.3\ wt.\% Fe_2O_3$  [45]. It was also discovered that, at the composition near the morphotropic phase boundary, where  $Fe_2O_3$  doping is over  $0.8\ wt.\%$ , particles containing  $Fe^{3+}$  ions would precipitate at grain boundaries, and that properties of the ceramic materials would deteriorate. Thereby,  $Fe^{3+}$  ions can restrain the grain growth, because the solid-solution limit of iron in PZT is about  $0.8\ wt.\%$  and the remaining iron ions are 'squeezed' out of grains and accumulate at grain boundaries.

On the other hand, some dopants (e.g.,  $CeO_2$ ) in PZT and  $PbTiO_3$  ceramics are helpful for grain growth. In a system with the composition  $PbTiO_3 + 3\ mol.\% PbNb_2O_6 + 0.5\ wt.\% MnO_2 + x\ mol.\% CeO_2$ , it was

observed that the grain size of the ceramics doped with  $0.5\ mol.\% CeO_2$  is smaller than that with  $5\ mol.\% CeO_2$  [46].

It is obvious that the grain size will affect the properties of piezoelectric ceramics. Figures 3.17a, b, c show experimental results for disk samples with the composition  $Pb(Zr_{0.51}Ti_{0.49})O_3 + 0.1\ wt.\% MnO_2$  at a constant density of  $7.70-7.85\ g/cm^3$  [47]. In general, piezoelectric properties of ceramics increase approximately linearly with increasing grain size.

In PZT ceramics in a tetragonal phase (titanium-rich) and in  $PbTiO_3$  ceramics, both  $180^\circ$  and  $90^\circ$  domain walls exist. Usually,  $180^\circ$  domains are

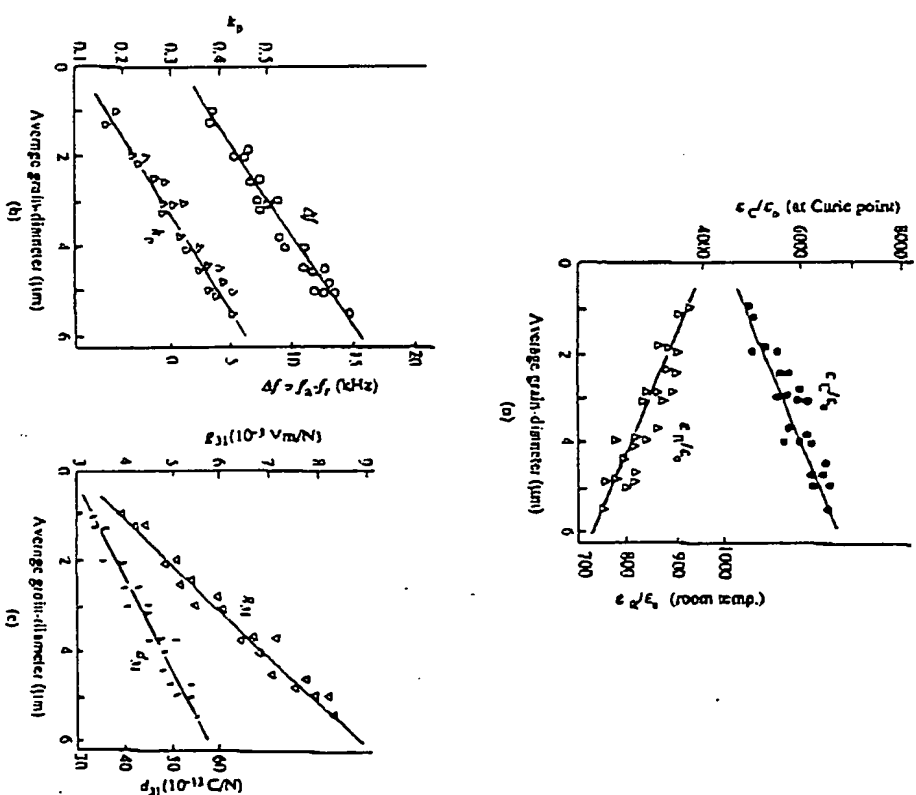


Fig. 3.17. Dependence of dielectric and piezoelectric properties on average grain size in the ceramic  $Pb(Zr_{0.51}Ti_{0.49})O_3 + 0.1\ wt.\% MnO_2$  (after Okazaki et al. [47]).